AC 2008-2371: QUANTUM DOTS: BRINGING NANOSCIENCE AND ENGINEERING INTO THE HIGH SCHOOL CLASSROOM

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Quantum Dots: Bringing Nanoscience and Engineering into the High School Classroom

Abstract

This study traces the lesson design process for a professional development initiative on nano-education. In particular, a lesson on quantum dots is traced throughout the iterative design process based on a learning performances framework combined with design-based research. Teacher feedback, pre- and post-tests covering conceptual information, and researcher field notes were used as the primary sources of data. From these data, themes were identified, and actions were taken to address each of these feedback themes to better correspond to the learning goals identified for the lesson.

Introduction

The face of science, engineering, and technology is rapidly changing. The biggest trends are also the smallest, as nano-scale phenomena prove to be more and more important in a wide range of applications. However, we still have yet to include these nano-scale phenomena in our secondary science curricula, leaving students unprepared to enter important careers in nanoscience, engineering, and technology.

Professional development efforts are one way to combat this issue. This study focused on curriculum design for a particular professional development program geared towards science teachers in grades 7-12. This professional development program was run through the National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) at Purdue University in summer 2007. This was the third year of the program, and another professional development institute will take place in summer 2008.

To address the design of lessons for professional development and future classroom use, the researchers used an iterative design process structured around learning goals and performances, basing revisions on teacher feedback and conceptual understanding. This paper will trace the iterative lesson design process, describing teacher feedback, assessments of conceptual understanding, and actions taken to improve the lesson based on this data.

Review of Literature

Nano-scale phenomena are playing a greater and greater role in every aspect of contemporary scientific research. Nanoscience, engineering, and technology (NSET) have wide-ranging applications in medicine, defense, development of electronics, environmental science, and materials science, to name a few.[1-3] It follows from this information that we will need many more workers in the nano-industries; one estimate suggests that the United States will need two million workers in NSET fields in the next decade alone.[4]

At the same time, the United States is experiencing the need for drastic reforms in science, technology, engineering, and mathematics (STEM) education. U.S. students do not measure up to many of their foreign counterparts on international assessments of science, and the number of doctorates awarded to U.S. students in STEM fields is steadily declining.[2, 5] These findings illuminate a need to infuse NSET education into the K-12 curriculum so as to prepare students for careers in STEM fields. Nano has been posed not only as a way to enhance the quality of U.S. STEM education in terms of content, but also as a means of increasing student motivation by presenting cutting edge developments in STEM fields and exposing students to possible future career opportunities.[6] Additionally, while many individuals in the general public are familiar with nano through informal means and have opinions on the topic, few have received formal education on topics pertaining to nanoscale science, engineering, and technology.[7]

Despite compelling arguments for inclusion of NSET into the K-12 curriculum, there is a paucity of research in this area. The little formal research that has been conducted has focused primarily on size and scale, including student and expert ideas about scale, and how to integrate ideas of size and scale into the classroom.[8-10] Other literature primarily consists of activities incorporating some NSET content, often at the undergraduate level[11] : very little is focused on inclusion at the secondary school level. To foster this inclusion, we must actively engage in the design of effective NSET curriculum materials and conduct research on the experiences of teachers and students with these materials.

In this paper, we approach the development of nano-scale educational materials from a learning goals perspective. Smith, Wiser, Anderson, & Krajcik suggest structuring curriculum around major ideas and practices in a discipline (learning goals) and codifying these in terms of "learning performances".[12] These learning performances can be tasks or activities appropriate for students in terms of building and demonstrating their understanding of important concepts. Additionally, the authors suggest using these learning performances to better structure assessments and to conduct research on student learning to inform curricular design.[12] This approach implies a "backwards design" for curriculum materials that is particularly appropriate for a complex topic such as quantum dots. With so many conceptual ideas already embedded in this topic, it is important to identify a few major big ideas (these will be the learning goals for our lesson), define learning performances, and focus activities and assessment within the lesson on these goals and performances.

This learning performances framework has other implications for lesson design. It emphasizes the use of research on student learning to inform changes in lesson structure and assessment. This formative approach to lesson assessment is compatible with a design-based methodological framework. As we collect lesson feedback and conduct pre- and post-tests focusing on conceptual understandings, we as curriculum designers can use this information to frame future iterations of the lesson and better address goals for learning.

Design-based research in education is formulated on the idea that by designing and implementing innovative educational materials in everyday settings, we can learn about the learning process itself.[13] Design-based research is characterized as iterative, process-focused, interventionist, collaborative, multilevel, utility-oriented and theory-driven.[14, 15] These seven key attributes are described with respect to this specific study in the methods section of this paper. Design-based research is also particularly appropriate for designing learning experiences that seem to be productive, but are not well-understood or researched.[14] NSET education is a prime example of such a discipline in which few educational interventions have been well-documented or studied in detail.

This type of research can proceed through a number of phases or steps. Collins, Joseph, & Bielaczyc provide a general methodological framework for carrying out design research.[16] This includes implementation, modifications, multiple ways of analyzing data measuring of variables, and reporting.[16] This is more succinctly summarized by Shavelson et al. as a cycle of designing/analysis/redesigning. This is the general methodological approach adopted by this study.[15] It is important to note that design research is utilized across disciplines. For example, design-based research has been successfully used in development of a program which allows students to create films.[16] While this approach is particularly appropriate for nanoscience education, it has been widely used across many fields and disciplines of educational research.

Design-based research is particularly effective at answering questions of what or why something is happening.[15] As we further explore the effects and limits of NSET educational implementation, these types of questions will move to the forefront of our inquiries. Limitations of the design-based approach stem from the dual role of researchers as advocates and critics of lessons, interventions, etc.; this is often addressed using multiple data sources for triangulation and repetition of analyses across the various cycles of iteration.[14] This limitation exists in our work with professional development; however, we attempt to address this limitation through triangulation of multiple data sources.

Purpose

The primary purpose of this study was to use information gleaned from a summer professional development initiative to inform the iterative design process of lessons based on learning goals. Based on this purpose, several primary research questions were identified:

1. What are the most important concepts in the quantum dots lesson that teachers believe can be implemented into their classrooms?
2. After experiencing a lesson, what do teacher feedback and conceptual knowledge tests tell us about effectiveness of the lesson?
3. Using an iterative, design-based approach, what kinds of changes can we make in response to teacher feedback and conceptual understandings?

These questions were addressed using a blend of design-based methodology and a learning performances theoretical perspective within the context of a nanoscience professional development program.

Context

This study was conducted within the context of a professional development initiative centered on nano-science, engineering, and technology (NSET) education. In 2007, thirteen teachers attended this professional development institute for a two week period, during which the teachers were exposed to a variety of topics through inquiry lessons, authentic NSET experiences (such as a visit to a clean room), seminars, and facility tours.

The teachers had all been teaching for at least three years when they attended the professional development institute, and all are science teachers in grades 7-12. However, within this group, they represent a wide variety of science disciplines, including middle school general science, biology, chemistry, physics, and integrated chemistry/physics. As a part of the professional development program, each teacher is required to implement one lesson from the program into their classroom. Members of the program staff maintain contact with the participants, and are often involved in observing in the classroom or assisting with implementation of nanoscience lessons. By following up with teachers, we are able to infuse feedback from learners and educators into our iterative curriculum design process.

In this study, the case of quantum dots was used as an example of iterative curriculum design for several reasons. First and foremost, quantum dots are a major area of current and projected future nanoscience research. With only two weeks to conduct a workshop on nanoscale phenomena, judicious choices must be made regarding content in order to cover the most high-impact topics. Quantum dots are integral to the field; therefore, finding a way to address them in a meaningful way during the professional development experience is important. Research on quantum dots will influence design of electronic displays, medical imaging, and specific diagnosis of many diseases, particularly cancer. They are versatile and easy to modify for use in vivo.[17] They also have properties that are size-tunable, which is a phenomenon unique to the nanoscale.[18] Additionally, quantum dots tie into the high school science curriculum for biology, chemistry, and physics in numerous ways, yet present practical challenges in terms of actual implementation. The topic is very complex and requires a fairly in-depth science background to fully understand. The actual synthesis is too dangerous/costly for actual implementation in the high school classroom, which points to a need for creative means of implementation. Finally, there is little to no literature available on the teaching of quantum dots, and what little exists is confined primarily to undergraduate education.[11] Therefore, there is a need to develop ways of integrating quantum dots into the curriculum that are meaningful and practically possible.

Methods

The quantum dots lesson for the professional development institute is structured around three major goals:

1. To tie fundamental concepts of biology, chemistry, and physics (such as the relationship between wavelength and energy) to the science behind quantum dots, thereby building a conceptual understanding of how quantum dots function.
2. To describe the unique size-dependent properties of quantum dots.
3. To expose teachers to a variety of important applications of quantum dots.

Based on these goals, a lesson was developed with three primary phases for the summer 2007 professional development institute. The first was a synthesis, where teachers would synthesize cadmium selenide quantum dots based on an established protocol.[19] As teachers completed the synthesis, they witnessed firsthand the time-dependent nature of the quantum dot color change. The second phase was a more in-depth investigation of the properties of quantum dots. The teachers used Spec 20s, TEM images (taken beforehand), and an online simulation to construct relationships between quantum dot size and color. The final phase was a group presentation, in which teachers would create a presentation for a fictional “company” in the area of biosensors, LEDs, or medical imaging, describing the use of quantum dots in their specific field. This approach was designed to target the three goals described previously.

This lesson was first implemented in summer 2007, and some deviations to the planned lesson occurred. The most important of these was the elimination of the presentation component of the lesson. This decision was made based on the desire to keep outside work for teachers at a level that was acceptable to them; however, the elimination of this component refocused the lesson away from applications and to isolated synthesis and simulation components, which dealt only with the scientific phenomena outside of any real-world situation. The presentation component contextualized the use of quantum dots in terms of their applications as a supportive technology in a variety of fields. Without this application/presentation component, teachers were not exposed to any meaningful contextualization of quantum dots in real-world applications. While it is difficult to say exactly how the presentation/application component would have impacted the overall quantum dots lesson experience for the teachers, it would take the first step of introducing applications of quantum dots. This would possibly help teachers contextualize quantum dots not only within contemporary science and technology, but within their own curricula. Additionally, unexpected challenges arose in the use of the spectrometers and the online simulation, raising new questions about lesson design and our own conceptual understandings of quantum dots. These changes were noted in detailed field notes by the researcher and provide valuable information in terms of creating a second iteration of the lesson.

Several sources of data were used in the iterative design process of this lesson. These data sources included anonymous teacher feedback forms, pre- and post-institute conceptual tests, and field notes taken during implementation and group discussions of the lesson and how it might be implemented into the classroom. Teacher responses on the conceptual pre/post-test and on the anonymous feedback forms were coded using an open coding approach, grouped into themes, and the major themes were developed into three assertions. Observational data in the form of field notes served to triangulate data collected directly from the teachers and substantiate the findings. All of the data sources contributed in a meaningful way to the second iteration of the lesson design, which will be described in the results section.

The observational data was primarily intended to look for discrepancies that might arise between test results and teacher feedback. We were primarily looking for comments relating to content knowledge (both comments that indicated how well teachers understood the lesson, and about teachers' beliefs about their own content knowledge). Additionally, we were interested in teachers' ideas about where quantum dots might fit into their pre-existing curricula, which was also addressed on the teacher feedback forms. Two researchers took field notes, and compared these to teacher feedback and pre- and post-test data. No major discrepancies were found in this iteration; however, we will continue to employ this methodology for purposes of triangulation.

The methods for this study as described above represents the seven key aspects of design-based research identified previously: the process is iterative, process-focused, interventionist, collaborative, multileveled, utility-oriented, and theory-driven.[15] This process is iterative; as we develop lessons for professional development, we continually engage in the design/analyze/redesign cycle to progress towards the accomplishment of our learning goals. It is process-focused in that we are attempting to trace over time our group of participants' progress in conceptual understanding and attitudes towards classroom implementation through feedback and pre-/post-tests. As we identify patterns, we will be able to assess the impact of our lesson on teachers' learning and thinking. Our research is both interventionist and collaborative in that we are attempting to modify real-world classroom settings by implementation of NSET lessons, and working with our participants, the classroom teachers, as valued partners in this process. This development process is collaborative and multileveled in that our work is focused on effective implementation, with links to implementation on university and secondary school levels. Finally, our research is theory-driven in that we are testing the effectiveness of this design/analyze/redesign process in terms of its effectiveness in development of our quantum dots lesson.

It is important to note that this is merely the first step in the iterative design process. We anticipate that this work will proceed through multiple iterations, and the first year's data represents our first iterative cycle. Each year, the process will continue as we engage in the analysis and redesign components of the design cycle.

Results and Discussion

Based on the teacher feedback, pre- and post-test answers, and researcher field notes, several major themes emerged from the data that contributed to the iterative lesson design process. These assertions will be presented along with the actions that are being taken to address them in the second major iteration of the lesson, to be presented to teachers during the professional development institute in summer 2008.

Assertion 1: Conceptual understanding grew between the pre- and post-tests, but teachers were unable to provide a deep explanation for the connection between dot size and band gap.

In a pre/post test of conceptual understanding, teachers responded to a series of questions that addressed each of the lessons in the institute. One of these questions addressed the relationship between size and color in quantum dots. Teachers were asked to tell whether a red or a violet quantum dot was larger in size based on provided energy level diagrams, and to explain their answer. From these responses, we were able to gather important data relating to the effectiveness of our lesson. Results from the pre- and post-tests are summarized in table 1.

	Pre-test teachers (percentage)	Post-test teachers (percentage)
Provided correct answer (red)	4 (33%)	10 (83%)
Provided incorrect answer (violet)	5 (42%)	2 (17%)
Provided neither answer	3 (33%)	0 (0%)
Cited a reason for correct answer based on band gap	1 (88%)	6 (50%)
Answer based on guesswork	5 (42%)	0 (0%)

Table 1: Summary of pre- and post-test results

Between the pre- and post-tests, more teachers were able to correctly identify that the red quantum dot was bigger. Additionally, the detail in answers was significantly greater on the post-test. Interestingly, only one teacher in the post-test used the experiment to justify his or her answer, as they responded that "the size of dots mutated with time= we started with small dots=yellow, end larger dots more reddish". Others appeared to have memorized the correct answer or did not provide an explanation ("The red is bigger"), or cited theoretical/mathematical explanations with varying degrees of accuracy and some circular reasoning involving the band gap issue (for example, "Red has the bigger size, because it has a smaller band gap. Therefore less energy = longer wavelength."). Given the percentage of time spent on the synthesis (high) to its apparent utility in explaining quantum dots (low), the finding that the experiment played a minor role in explanation is significant. This has prompted us to reconsider time distribution within our lesson.

On the post-test, teachers' conceptual understanding was significantly more developed from the pre-test. In particular, five more teachers provided reasoning for a correct answer based on band gap. However, only one teacher was able to provide a reasonable answer for why the band gap itself is smaller in larger dots. The participant responded, "The red dot is larger because as the dot grows in size, the band gap gets smaller. This means that electron transitions between valence and conduction will produce lower energy photons which are red. Why the band gap gets smaller is a much more difficult question that I think has something to do with the fact that a larger dot has more allowable states and a lower energy density causing the smaller band gap." This was our most sophisticated response in terms of conceptual understanding; however, the fact that it was the only one of its kind was illustrative of the lack of conceptual depth in the lesson.

The lack of sophistication in responses may be a result of several factors. First, as this was an initial effort at implementation, the professional development team realized that we still had many questions about the science behind quantum dots, and were unable to explain them in as much detail as we would have liked. Second, the lesson focused primarily on construction of basic relationships, and did not press the teachers to go into great detail about the band gap issue. Depending on background, this would have required a great deal of time to fully explain, so we made the decision to focus on basic relationships instead. However, this seems to have left our teachers with many questions about the origin of the quantum dots phenomenon.

The teachers themselves agreed that they didn't attain adequate conceptual understanding of the quantum dots phenomenon in this lesson. This is particularly significant given data that indicate that when teachers are more comfortable with content, lessons are planned in a more organized way, with more opportunities for students to engage in critical thinking, and goals of the lesson are more conceptual than factual.[20] Additionally, teachers with more developed content knowledge are more likely to customize activities for their learners to take into account their prior knowledge and focus lessons around important themes.[21] Given these findings and our eventual goal of grades 7-12 classroom implementation, equipping teachers with a strong foundation of conceptual understanding is paramount.

Many teachers wanted deeper explanations of the relationship between size and color, and four out of twelve mentioned this specifically on their feedback forms. Several participants suggested a tutorial at the beginning to, as one teacher commented on the feedback form, "help the topic to become less conceptually opaque". Teachers were interested in furthering their knowledge of this topic; prior to the discussion period the following day, several of the teachers completed a detailed list of questions on various conceptual issues surrounding quantum dots. Some of these we were able to address, but others revealed our own misunderstandings about the topic. This revelation about our own content knowledge led us to explore the topic more in-depth and challenge our underlying ideas about the quantum dots phenomenon.

In our next iteration of this lesson, we are attempting to address this issue by first clarifying our own conceptions of the relationship between band gap and particle size. This is a fairly complex relationship, and as a team we have begun to "unpack" the major concepts behind our lessons. This will help us to identify the true "main ideas", and structure the lesson more clearly around the most important concepts, articulated as learning goals. This approach is consistent with design-based research on learning goals as described by Smith et al.[12] To assist in this process, we have consulted with practicing engineers and scientists who conduct research in the area of quantum dots. As we clarify our primary learning goals, we can use a backwards-design approach to reshape our lesson around these objectives. We will also re-integrate the presentation/application component of the lesson. This will allow teachers an opportunity to fully synthesize their findings and present them to the group. The presentation will then serve two purposes: it will allow the teachers the opportunity to work through their findings about individual relationships involved in quantum dots (for example, relationship between size and color, size and band gap) and hopefully better understand how these all work together, and it will serve as a formative assessment, allowing both NCLT program staff and teachers to more immediately understand where gaps in understanding may exist.

Assertion 2: While teachers enjoyed the quantum dots lesson as an experience, they had difficulty seeing where it could fit into their curriculum.

Most of the teachers commented on the feedback forms that the synthesis of quantum dots was a positive experience, describing it as "interesting", "cool", and "entertaining, and frequently referencing the "wow" factor associated with the synthesis and viewing the quantum dots under the UV light source. However, the majority of teachers commented that they could not implement the synthesis into their classroom, and therefore wouldn't necessarily be able to use the lesson. We had never intended the implementation of the synthesis into the high school classroom because of safety considerations; however, the fact that teachers repeatedly commented on the dangers of the synthesis reveals that we likely did not emphasize the role of the synthesis as an authentic NSET experience for the teachers only. Therefore, it follows that we likely did not emphasize the critical components for classroom implementation strongly enough. It is significant that most teachers had a difficult time making connections to their standards-based curricula, as data has shown that teachers are less likely to implement curricular materials when this is the case.[20] One teacher summed their difficulty in balancing their interest in the topic with practical considerations. On the feedback form, the participant wrote, "This is possibly the area of nanoscience in which I have the most interest (from a physics perspective), so I would love to use it in the classroom if I can fit it in, but my knowledge is very limited and resources are hard to come by". This general attitude was also echoed in the group discussion from the researcher's field notes- teachers seemed to enjoy the experience, but were at a loss when it came to actual implementation.

To address this component of the teacher feedback, the professional development team is planning to de-emphasize the synthesis component of the lesson, as it does not directly address the learning goals (i.e. the goal is not to gain experience in chemical synthesis, although some of the observations contribute to building the relationship between size and color of quantum dots). In the second iteration of the lesson, the actual synthesis will be replaced by relevant video clips, and provided TEM images. The focus will be shifted to the simulation component, which is more usable in a secondary classroom, and the application/presentation component. This will provide more closure to the lesson and allow teachers the opportunity to synthesize the data that they collect and make sense of it. Additionally, while teachers work on their presentations, they will have opportunities to interact with members of the professional development team and discuss conceptual questions in small groups. The post-lesson discussion period will also be more directed towards means of classroom implementation to provide a more organized forum for teachers to reflect on implementation.

It is important to note that although we were interested in exploring how teachers connected concepts from quantum dots to their curricula (research question 1), we were not able to fully answer this research question during the first iteration of the lesson. This can be attributed to the fact that teachers had a difficult time understanding both the concepts involved and the overall purpose of the lesson. We hope to be able to better address this question after we implement the second iteration of the lesson in summer 2008, and begin a new cycle in the iterative design process.

Assertion 3: Teachers found the lesson disjointed, and had a difficult time connecting the various components of the lesson.

While the teachers were able to successfully complete the synthesis of quantum dots and the simulation, many of the teachers had a hard time identifying an overall purpose for the lesson. During the post-lesson discussion, teachers raised concerns about the relationship of the simulation to the synthesis lab. One suggestion from the feedback forms addressing this was that "the simulation could be done before the synthesis so we had an idea of the goal in mind". Many teachers also suggested use of video clips embedded in the simulation to assist with these connections as well. We plan to utilize this in place of the synthesis itself, although teachers will still be able to examine the quantum dots that we synthesize prior to the professional development institute.

Teachers also wanted more of a "payoff" at the end- while they could complete each of the components, several teachers mentioned that beyond the "wow factor", they had collected a good deal of information that they did not use in any way. Based on these general trends in the feedback and discussions, actions will be taken to establish a more coherent flow in the lesson and tie together the simulation and synthesis. One way to do this is to implement the application component of the lesson, which will require teachers to draw on the information they gleaned from experimentation with the quantum dots and the simulation. In this application component, the teachers will create a presentation for a fictional "company" that wants to use quantum dots, explaining a) how they function and b) why they would be useful for this particular application. This component will tie together the various aspects of lesson and allow teachers to take home the big picture of quantum dots.

Summary of Actions

Based on the feedback summarized in the results section, several actions have been taken in the second iteration of the lesson to promote the achievement of identified learning goals. As we engage in this iterative, design-based process, the actions we have identified will allow us to better structure the lesson around our previously identified learning goals. Table 2 summarizes the learning goals, feedback relating to these goals as summarized in the assertions, and actions taken to better achieve these learning goals. Representative quotes for each section are also provided to illustrate the types of feedback that were utilized in developing the assertions.

Learning Goal	Feedback	Representative quote	Action
Connecting quantum dots to various traditional fields of school science	Assertion 2- Connections unclear when made at all- don't fit into curriculum	"Even though I wouldn't do the lab in class I'm glad I had a chance to try it- Cool!"	Shift away from synthesis and emphasize simulation and presentation/ application components for classroom use
Describe size-dependent properties of quantum dots	Assertion 1- Difficulty connecting size and band gap/color of dot- explaining why exactly size should influence band gap	"Need more info on why/how the color changes with size" Test response: "Red has the bigger size, because it has a smaller band gap. Therefore less energy= longer wavelength."	"Unpacking" of concepts to solidify our own understanding, construction of learning goals, and design of learning performances to specifically target these goals.
Describe applications of quantum dots	Assertion 3- Desire for something to "tie it together"- comments about application often absent due to lack of implementation	"A lot of us were unsure of the overall purpose." "This activity needs more 'payoff' at the end- after the dots were created everyone said 'ooh' and 'ahh' but that was about it."	Implementation of the "application" portion of the lesson, where teachers will use information from each part of the lesson to create a presentation.

Table 2: Summary of feedback and actions

The shift from isolated experiences with the synthesis and simulation to a full lesson structured around a final presentation is intended to allow teachers a formal way to make connections to the real world and to their classrooms. This is an important step towards achieving the first learning goal. For example, teachers will need to formally discuss the relationship between color and energy in quantum dots, which can be connected to most chemistry and physics curricula. Additionally, the presentation component is something that fits well into a high school classroom, whereas the synthesis is not something the teachers could take into their classrooms without major modifications (and likely, it would not be possible). This is a shift from a "cool nano experience" to a meaningful classroom lesson.

Unpacking our own understandings will better prepare us to address the second learning goal, as we will now be better equipped to answer questions that arise during the lesson. Additionally, our new understandings of the quantum dots phenomenon has allowed us to restructure our lesson using a backwards design approach; the major concepts identified in the unpacking have been formulated into sub-learning goals, and from there we have developed tasks and a formative assessment (presentation/application) component to ensure that we are meeting these sub-goals.

The final learning goal will be directly addressed by the re-integration of the presentation component. This will require teachers to read scientific literature and popular news articles about quantum dots applications. While we can't be sure of the success of this approach until we implement the second iteration, exposing the participants to applications through research articles and asking them to present their findings will be a first step towards helping them connect the phenomenon to the applications.

Conclusions

The example of quantum dots is a meaningful one in terms of describing curricular design. The implementation of cutting-edge NSET topics into K-12 classrooms is a relatively new phenomenon, and thus provides us with the opportunity to design curricular materials in a new way. The iterative design process allows us to infuse feedback from teachers to better meet their needs as science educators in a rapidly changing field. While the quantum dots lesson is a particularly illustrative example, given its inherent difficulties in both conceptual understanding and implementation, this process can be applied to numerous other topics relating to nano-scale phenomena: ferrofluids, biosensors, lithography, and many others. The development of this approach to curriculum design for new content also has implications for curriculum design in other emerging fields that do not relate to NSET topics; for example, the increasing emphasis on teaching global climate change.

This work is merely the first step in answering our primary research questions. Design-based research goes through numerous iterations, and this is only the first of many. A second major iteration will be implemented with participants in summer 2008, and after that we will reengage in the analysis and redesign processes. In our next iteration, we hope to be able to better begin to answer our first research question dealing with participants' connections of content to curricula. We have gleaned a great deal of useful information relating to our second research question, utilizing teacher feedback and pre- and post-tests to reconceptualize our lesson around learning goals. Our third and final research question, regarding the changes that can be made in the lesson based on feedback, has been summarized in the summary of actions section. This will evolve as we continue to engage in the iterative design process.

As we select the most important high-impact topics in nanoscience, engaging in this design-based approach to lesson development will be necessary to establish a cycle of constant improvement and implementation. By engaging in this cycle of design, we can optimize the effectiveness of NSET education in secondary science, and extend this approach to new initiatives in science, engineering, and technology curricula.

References

1. Sweeney, A. E.; Seal, S.; Vaidyanathan, P., The promises and perils of nanoscience and nanotechnology: Exploring emerging social and ethical issues. *Bulletin of Science, Technology & Society* **2003,** 23, (4), 236-245.
2. Foley, E. T.; Hersam, M. C., Assessing the need for nanotechnology education reform in the United States. *Nanotechnology Law & Business* **2006,** 3, (4), 467-484.
3. Merkle, R. C., It's a small, small, small, small world. *Technology Review* **1997**.
4. Chang, C.-Y., The highlights in the nano world. *Proceedings of the IEEE* **2003,** 91, (11), 1756-1764.
5. National Academy of Sciences; National Academy of Engineering; Institute of Medicine, *Rising above the gathering storm: Energizing and employing America for a brighter economic future*. The National Academy Press: Washington, D.C., 2007.
6. Chang, R. P. H., A call for nanoscience education. *Nano Today* **2006,** 1, (2), 6-7.
7. Bainbridge, W. S., Public attitudes toward nanotechnology. *Journal of Nanoparticle Research* **2002,** 4, 561-570.
8. Tretter, T., Conceptualizing nanoscale. *The Science Teacher* **2006,** 73, (9), 50-53.
9. Tretter, T. R.; Jones, M. G.; Andre, T.; Negishi, A.; Minogue, J., Conceptual boundaries and distances: Students' and experts' concepts of the scale of scientific phenomena. *Journal of Research in Science Teaching* **2006,** 43, (3), 282-319.
10. Tretter, T. R.; Jones, M. G.; Minogue, J., Accuracy of scale conceptions in science: Mental maneuverings across many orders of spatial magnitude. *Journal of Research in Science Teaching* **2006,** 43, (10), 1061-1085.
11. Hutchins, B. M.; Morgan, T. T.; Ucak-Astarlioglu, M. G.; Williams, M. E., Optical properties of fluorescent mixtures: Comparing quantum dots to organic dyes. *Journal of Chemical Education* **2007,** 84, (4), 1301.
12. Smith, C. L.; Wiser, M.; Anderson, C. W.; Krajcik, J., Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and atomic-molecular theory. *Measurement* **2006,** 4, (1-2), 1-98.
13. Bell, P., On the theoretical breadth of design-based research in education. *Educational Psychologist* **2004,** 39, (4), 243-253.
14. Design-Based Research: An Emerging Paradigm for Educational Inquiry. *Educational Researcher* **2003,** 32, (1), 5-8.
15. Shavelson, R. J.; Phillips, D. C.; Towne, L.; Feuer, M. J., On the Science of Education Design Studies. *Educational Researcher* **2003,** 32, (1), 25-28.
16. Collins, A.; Joseph, D.; Bielaczyc, K., Design Research: Theoretical and Methodological Issues. *Journal of the Learning Sciences* **2004,** 13, (1), 15-42.
17. Wang, X.; Ruedas-Rama, M. J.; Hall, E. A. H., The emerging use of quantum dots in analysis. *Analytical Letters* **2007,** 40, (8), 1497-1520.
18. Alivisatos, A. P., Semiconductor clusters, nanocrystals, and quantum dots. *Science* **1996,** 271, 933-937.
19. Boatman, E. M.; Lisensky, G. C.; Nordell, K. J., A safer, easier, faster synthesis for CdSe quantum dot nanocrystals. *Journal of Chemical Education* **2005,** 82, (11), 1697-1699.
20. Gess-Newsome, J., Secondary teachers' knowledge and beliefs about subject matter and their impact on instruction. In *Examining pedagogical content knowledge: The construct and its implications for science education*, Gess-Newsome, J.; Lederman, N. G., Eds. Kluwer Academic Publishers: Boston, 1999; pp 51-94.

21. Hashweh, M. Z., Effects of subject-matter knowledge in the teaching of biology and physics. *Teaching & Teacher Education* **1987,** 3, (2), 109-120.